"IN SITU" MEASUREMENT OF NEGATIVE PORE PRESSURES IN SOILS.

JAMES HAROLD OSBORN

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A

TECHNICAL REPORT

by

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Submitted to Texas A&M University in
partial fulfillment of the requirements for the degree of

Master of Engineering

January, 1967

Major Subject: Civil Engineering

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January, 1967

ACKNOWLEDGMENTS

This writer is particularly indebted to Dr. W. A. Dunlap and Dr. J. R. Runkles for suggesting the field of research and for their assistance, both moral and financial. Professor S. J. Buchanan was also of great help, being a ready source of information concerning the problem of negative pore water pressures. His financial assistance and moral support is also appreciated. C. F. Raba is also to be commended for his ready assistance in providing laboratory equipment.

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INTRODUCTION

The greater portion of the earth's surface that is used by man is covered by soil which is in a partially saturated state (a three-phase system consisting of soil grains, water and air). To the soils engineer this means that design should be predicated upon a theory taking into account the various parameters that affect the shear strength and volumetric stability of this type soil mass. To the agronomist this means that the study of plant life should consider the changes in availability of water to the plant from this soil. It has been determined that all of these parameters are a function of what is called pore water pressure in the soil mass. As will be discussed later in the paper, this pore water pressure is negative (tensile) in magnitude, and in active clay soils, it tends to increase its shear strength and volumetric stability while it adversely affects the ability of a plant to withdraw the soil moisture necessary for life.

Unfortunately, however, there is no satisfactory method now available that permits "in situ" measurement of the negative pore water pressures. As a result, the engineer and agronomist are limited in obtaining a complete understanding of this phenomenon; hence, no satisfactory principles have been evolved to establish useable criteria in this field. Both are basically dependent on empirical methods that have "proved right" over a period of years of trial and error.

One of the basic problems in measurement of these pore pressures is that they are negative and involve water. Since water cavitates at a theoretical lower pressure limit of -14.7psi, accurate measurement is no longer possible without elaborate equipment and precise controls. This mandates a laboratory environment.

There are many chemical compounds that have an affinity for water and also swell upon adsorbing the water. By finding a chemical compound with suitable characteristics and enclosing it suitably, the total negative water pressure (capillary, osmotic, induced dipole,

van der-Waals, etc) can be converted into a positive pressure and the measurement problem no longer exists.

It is the purpose of this paper to establish a testing method to examine some chemical compounds that have an affinity for water with the hope that the information gained will lead others to devise an easy and reliable method for measuring the "in situ" pore water pressures found in partially saturated soils by the use of the principle of pressure conversion.

BACKGROUND

PHYSICS OF A PARTIALLY SATURATED COHESIVE SOIL MASS

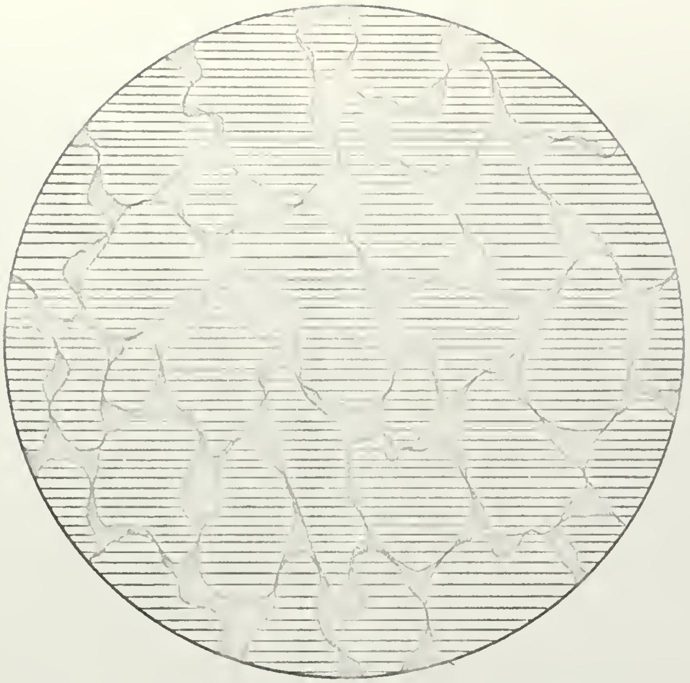
The total pressure acting in a soil mass is made up of several contributing factors, all of which are measured by the proposed method of pressure conversion. This total pressure can be expressed in terms of the free energy of the soil water relative to free pure water, and is usually expressed as an equivalent potential or suction. This total suction is that suction in pure water that will cause the same free energy reduction at the same temperature, and may be considered to be dependent on two things:

a. Matrix or soil water suction. The negative gage pressure relative to the external gas pressure on the soil water to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water.

b. Osmotic suction. The negative gage pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable membrane (permeable to water molecules only) with a pool containing a solution identical in composition with the soil water.

In actuality, there are gravitational and external gas pressure potentials that are also a part of this total suction, but they may usually be neglected.[1]

Now, let us consider the factor of capillary pressure in the soil water total suction. Consider a mass of soil that is totally saturated, i.e., all the voids in the mass are filled with water, Figure 1. These voids are interconnected in such a manner that they may be considered to be a series of capillary tubes extending from one end of the soil mass to the other. These tubes may also be considered to be of a relatively constant diameter, though this is hardly the case in actual soils. Now as the mass is subjected to drying, the familiar water-air meniscii form in the capillary tubes. As drying continues, the radii of these meniscii decrease, Figure 2. The surface tension



TWO PHASE SOIL SYSTEM

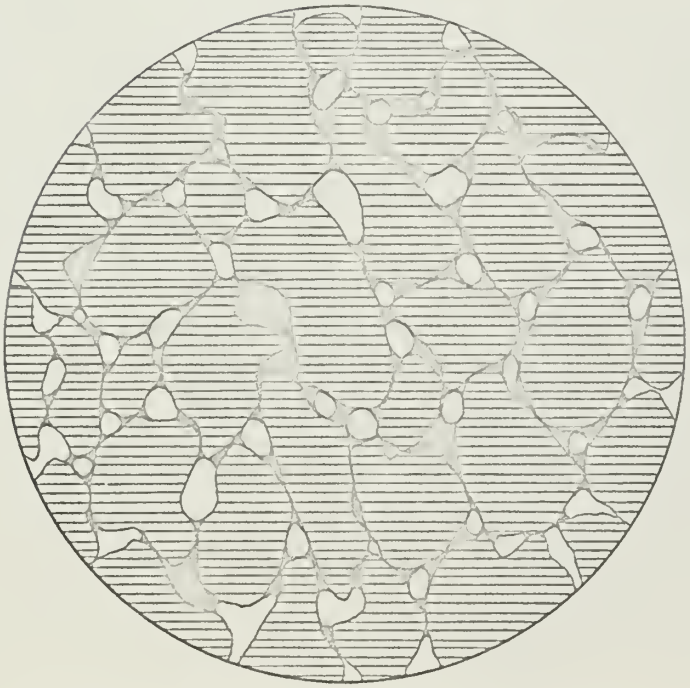
FIGURE 1

▤ SOIL

░ WATER

☐ AIR

FIGURE 2



THREE PHASE SOIL SYSTEM

of the water in these capillaries and the air-water interaction combine to induce a state of tension in the water. This tension or capillary pressure is defined by the equation

$$U_c = \frac{-2T_s(\cos \alpha)}{r}$$

T_s = surface tension of water (constant as far as the limits of engineering practice is concerned)

α = contact angle between water and the capillary tube (normally considered to be zero because the capillary water is in contact with the adsorbed water on the soil grains)

r = mean of the two principle radii of meniscus

It can be seen that as the soil dries, the capillary pressure becomes increasingly larger in magnitude.[2]

There is a second interaction that contributes to the soil water suction of this soil system. Low and Deming in 1953 presented three mechanisms that tend to produce tensile stress in the free soil water:

a. the tendency to reduce the difference in the cation concentration in the developed double layers around the soil particles (osmotic pressure);

b. the attraction of permanent and induced dipoles in the water molecules towards the soil surface, caused by the existence of the negative electric field in the proximity of the soil particle.

c. van der-Waals attraction (dispersion effect) between soil and water molecules.

In the past these three forces have been considered to be so small in comparison with the capillary pressure that they have been neglected.[3]

Let us look at the case of the induced dipoles of water in light of the results of some recent research. Consider an active clay such as sodium-ion montmorillonite. The water in such a soil exists in two phases, free water filling the pore spaces and adsorbed water attached to the negatively charged clay particle. The dipoles of water attach themselves to the particle creating an adsorbed water surface. Some feel that this adsorbed water film becomes water in a crystalline

state. The resultant film of water creates what is commonly known as a plastic clay. At the liquid limit of such a clay, it has expanded as much as possible, and, at the shrinkage limit, the clay is at its most compact state. As the clay moisture content decreases from the liquid limit, the free water is driven off and some of the outer layer of the adsorbed water is also lost. In this process the capillary pressure in the free water and the negative bond around the particle increase. The sodium-ion montmorillonite is considered to be very sensitive volumetrically over the range of moisture contents between the liquid limit and plastic limit. If one is to say that the only significant factor in volumetric stability is that of capillarity, then any material with the same particle size as sodium-ion montmorillonite will exhibit the same volumetric sensitivity and plasticity. Research conducted at Texas A&M University by Burk in 1964 used a rock flour whose particle size was the same as that of sodium-ion montmorillonite. The rock flour showed neither plasticity or any significant volumetric sensitivity. This tends to indicate that the negative pressure existing in a given active clay will become more and more dependent on the adsorbed water or induced dipole effect as dessication continues.[4]

PRINCIPLE OF EFFECTIVE STRESS

The principle of effective stress in saturated soils (a two-phase system of soil grains and water comprising the total volume of a given soil sample) as proposed by Terzaghi in 1923 has proved to be an effective and reliable tool in predicting the engineering behavior of this type soil. Terzaghi showed by experiment that

$$\sigma' = \sigma - U_w$$

σ' = effective stress (by definition, the stress controlling changes in volume or strength of a soil)

σ = total applied stress acting in a given direction at any point in the soil

U_w = water pressure present in the soil

and $U_W = U_a + U_c$

U_a = pressure in the air

U_c = equivalent suction[5]

This general equation is probably not strictly exact and it is probably far more complicated. In the case of saturated soil, however, it has proved to be an excellent approximation which is highly accurate as far as the soil engineer is concerned.[6]

In 1955, Bishop, et al, presented a tentative expression for an effective stress principle for partially saturated soils. The expression is

$$\sigma' = \sigma - U_1 + \chi(U_1 - U_2)$$

σ' = same term used in Terzaghi's equation

σ = same term used in Terzaghi's equation

U_1 = the pressure in the gas and vapor in the soil

U_2 = water pressure present in the soil

χ = variable (equal to 1 for saturated soils and zero for completely dry soils)

In 1960, Bishop discussed some of the limitations of the value χ. He stated that intermediate values of χ depend primarily on the degree of saturation S, but they are also probably influenced by factors such as soil structure, the cycle of wetting and drying or the change of stress level, etc., leading to a particular value of S. He proposed a graphical variation as shown in Figure 3.[7]

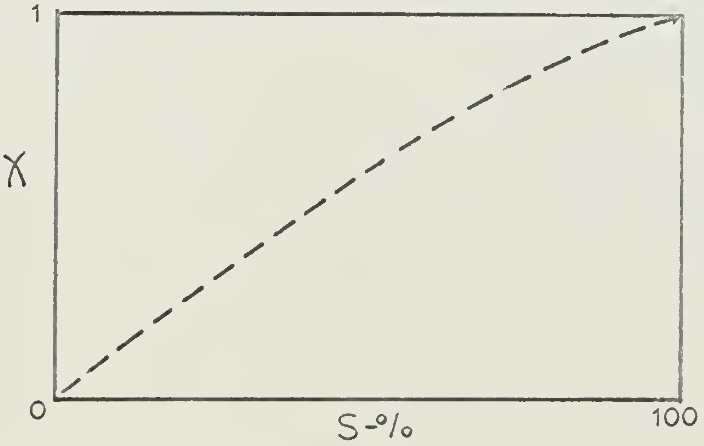


FIGURE 3

Studies made by Gulhati and Colman (1962) of Massachusetts Institute of Technology indicate that Bishop's proposed equation is inadequate since they found values for χ , as used in Bishop's equation, to be both greater than one and less than zero. These gentlemen recommend the use of a similar equation based on their observations:[8]

$$\sigma' = \sigma - U_a + (a_w + a_t)(U_a - U_w)$$

σ' = effective stress

σ = total applied stress

U_a = pore air pressure

U_w = pore water pressure

a_w = area of water per unit area (ratio of wet area to the total area of the wavy plane)

a_t = equivalent area ratio defined by the equation

$$a_t = \frac{F_t}{A(U_a - U_w)}$$

F_t = force due to surface tension at the air-water interface

A = area of wavy plane

As can easily be seen, this equation is the same as that proposed by Bishop with the exception that χ has been redefined.

Although there is some disagreement on the exact equation to be used in predicting the shear strength of a soil mass, it is agreed by all that the negative pore water pressure is a major factor in determining the strength of a soil mass.[9]

If a soil is compressed and drainage of the pore water is permitted, the volume change may be considered to be a function of:

a. compression of any gas present;

b. deformation of the soil skeleton.

Lamb (1958) showed that a soil skeleton will deform because of

a. particle diminution;

b. particle deformation;

c. change in size of the particle micelle;

d. particle rearrangement.

Generally, only particle rearrangement is considered to be the reason

for any measurable deformation.[10] It is essentially a function of the shearing resistance of a soil mass; the closer the packing, the more the strength. In the case of active clays, particle diminution is a major factor.[11]

Agronomists are interested in the negative pore pressure because of its serious effect on the ability of a plant to withdraw necessary moisture from the soil. As the negative pore pressure increases, the plant root system finds it more difficult to pull the water from the soil. When the pressure reaches the vicinity of -200 to -250psi or a pF of approximately 4.1 to 4.3, the root system of most agricultural plants cannot overcome the pressure causing the plant to wilt and die.[12]

METHODS OF MEASUREMENT OF NEGATIVE PORE WATER PRESSURE

The soil physicist has worked on methods to tell the agronomist when the negative pore water pressure becomes critical so that irrigation can be accomplished economically. Most of the methods explained below are a result of research in connection with the problem of the agronomist. Some of these methods can be used by the engineer when he needs pore water pressure information.

As previously mentioned, there is a theoretical lower limit of -14.7psi, beyond which water will cavitate and make measurement of pore water pressure very difficult. Some methods in use take advantage of the fact that when two or more substances are in equilibrium with each other, the specific free energies of all the phases are alike. The equipment merely has to measure the free energy of the immediately adjacent vapor in equilibrium with the soil mass and the total negative pore pressure is easily calculated from this known data.[13] It might be noted that all causes of negative pore water pressure will be considered when this method is used.

The total negative pore water pressure has been simplified to some extent by the use of the term pF. This term is defined as

$$pF = \log(h)$$

h= negative pore water pressure expressed in terms of the height of a column of water measured in centimeters.

TABLE 1[14]

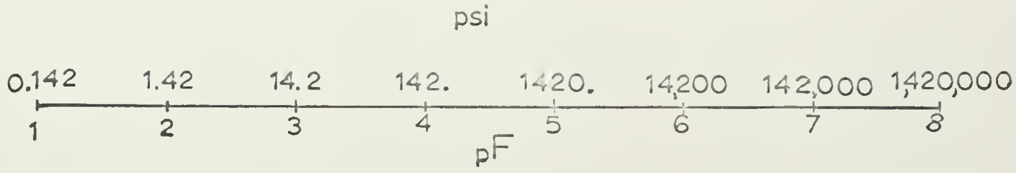


Figure 4 shows the relationship of pF to relative humidity. The limits of the present devices are given in Table 2 below.[15]

TABLE 2

METHOD	RANGE OF SUCTION
Tensiometer	0.0 to 3.3
Direct Suction	0.0 to 3.0
Suction Plate	0.0 to 3.0
Centrifuge	3.0 to 4.5
Vacuum Dessicator	5.0 to 7.0
Pressure Membrane	0.0 to 6.2
Psychrometer	2.0 to 5.0
Gypsum Block	2.5 to 4.2
Freezing Point Depression	3.0 to 4.0

Tensiometer: The tensiometer, Figure 5, consists of a porous block initially filled with water and surrounded by the soil sample. The block is connected to a mercury manometer by a water column. The soil water has a lower free energy than the water in the porous block causing water to flow from the block to the soil until equilibrium is reached. The equilibrium point is read on the mercury manometer and the moisture content of the soil is determined. By using a series of different initial moisture contents for a given soil, a soil free energy (suction) versus initial moisture content relationship may be obtained. This method is limited because of the possibility of

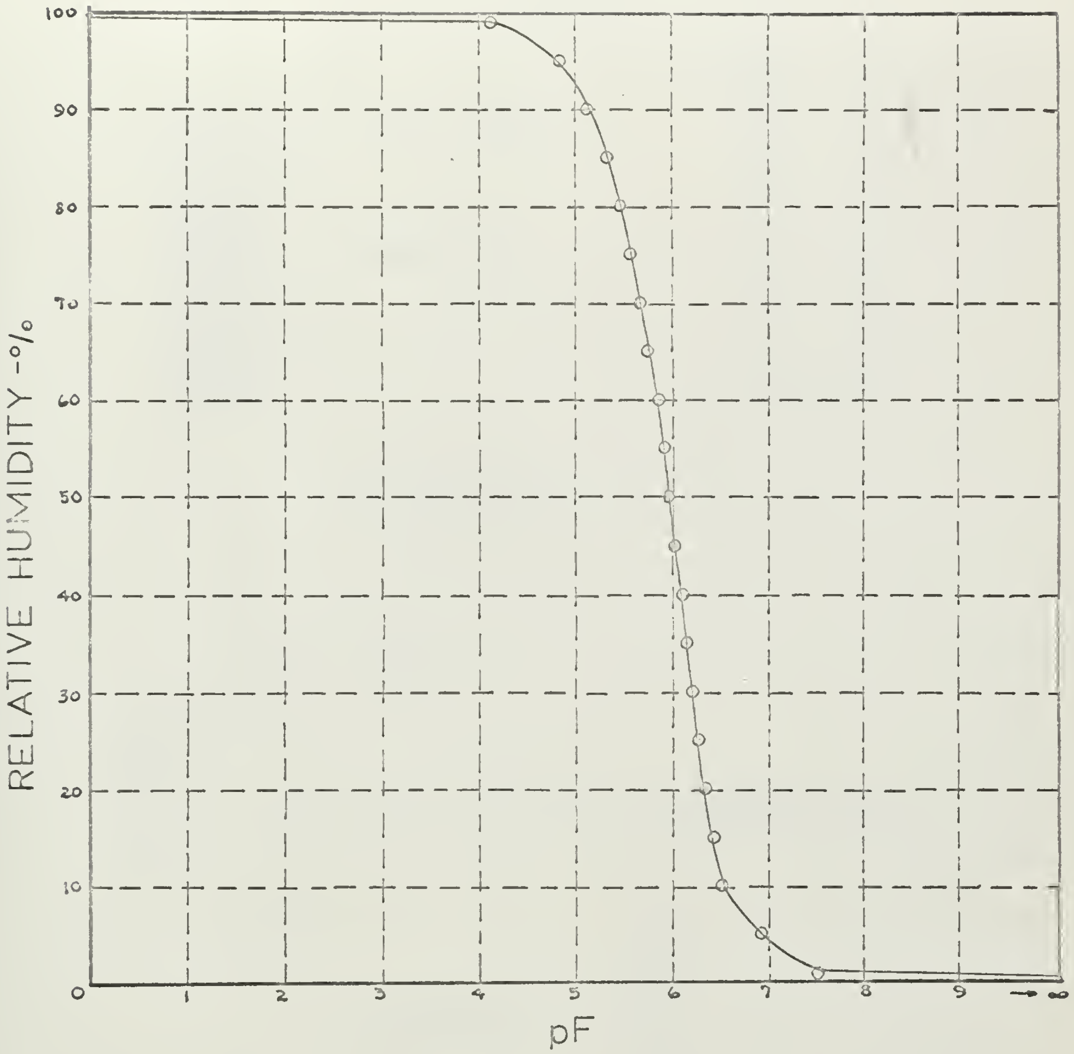
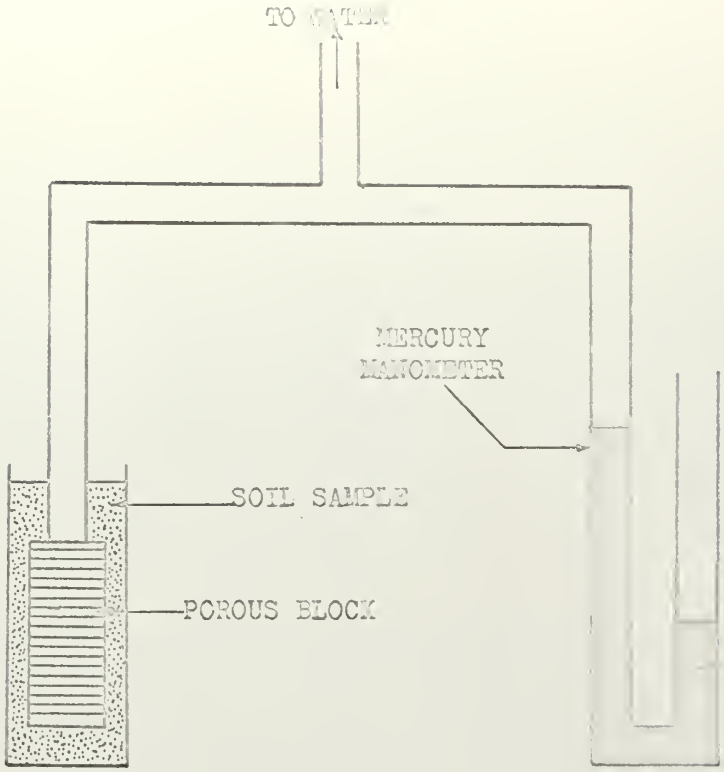
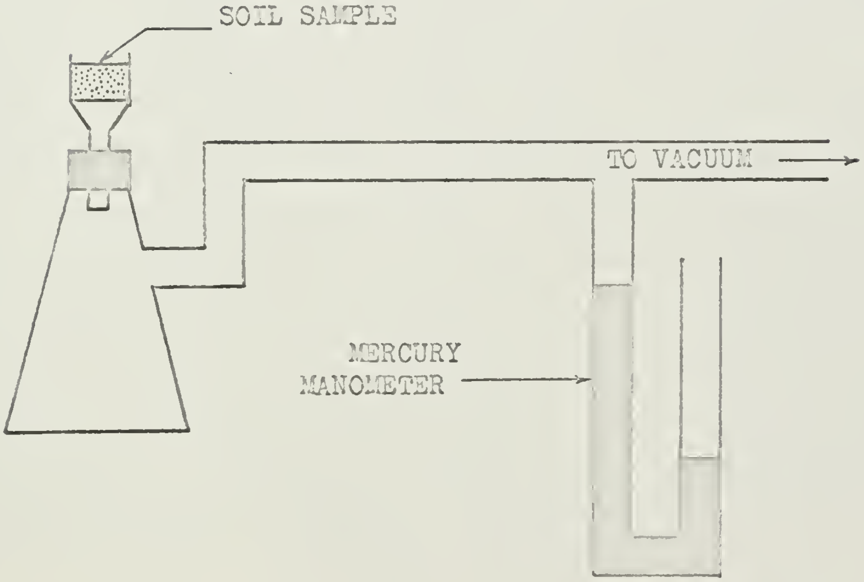


FIGURE 4



TENSIOMETER
FIGURE 5



DIRECT SUCTION
FIGURE 6

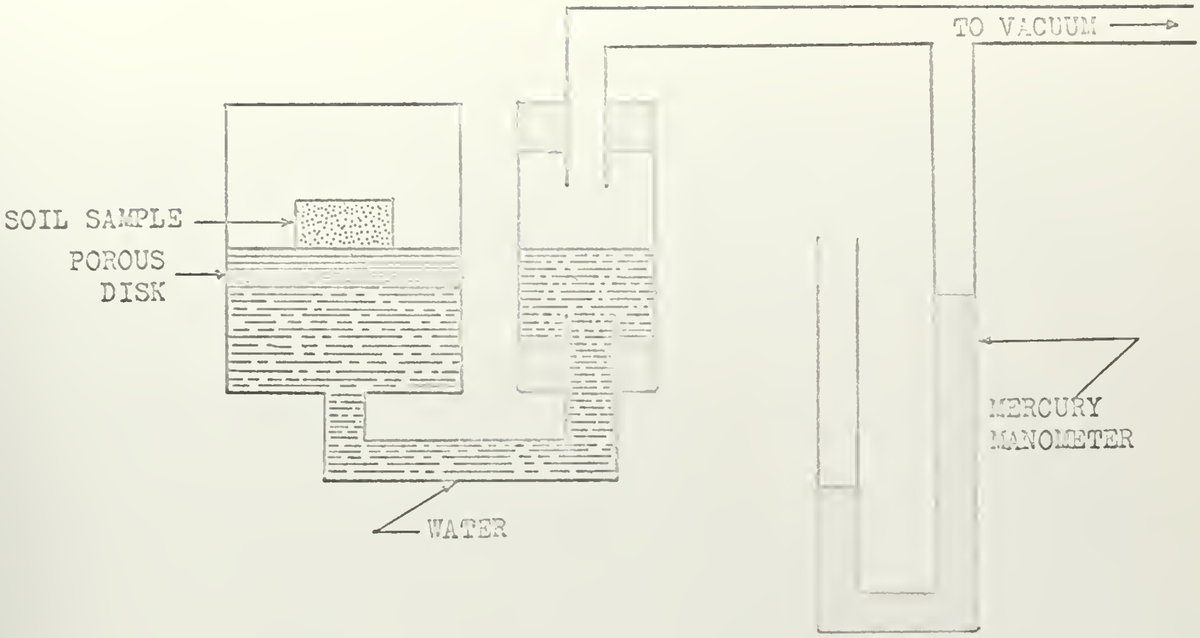
cavitation occuring in the water column.[16]

Direct Suction: The direct suction device, Figure 6, determines the soil suction of a soil sample during drying, the reverse of the tensiometer method. A known suction pressure is applied to a small soil sample until equilibrium is obtained. The moisture content is then determined and by a series of different initial suction pressure applications, a suction versus moisture content relationship may be determined for the given soil.[17]

Suction Plate: The suction plate method, Figure 7, is similar to the direct suction method with the exception that the soil sample is supported on a porous disk and the suction pressure is applied hydrostatically. The porous disk has an air entry value greater than 14.7psi. (air must be at a higher pressure than 14.7psi. before it will pass through the disk). The suction in the system is controlled and the moisture content of the soil sample is determined after equilibrium is reached. Again, a suction versus moisture content relationship may be determined. This process is applicable to both the wetting and drying cycle of soil moisture.[18]

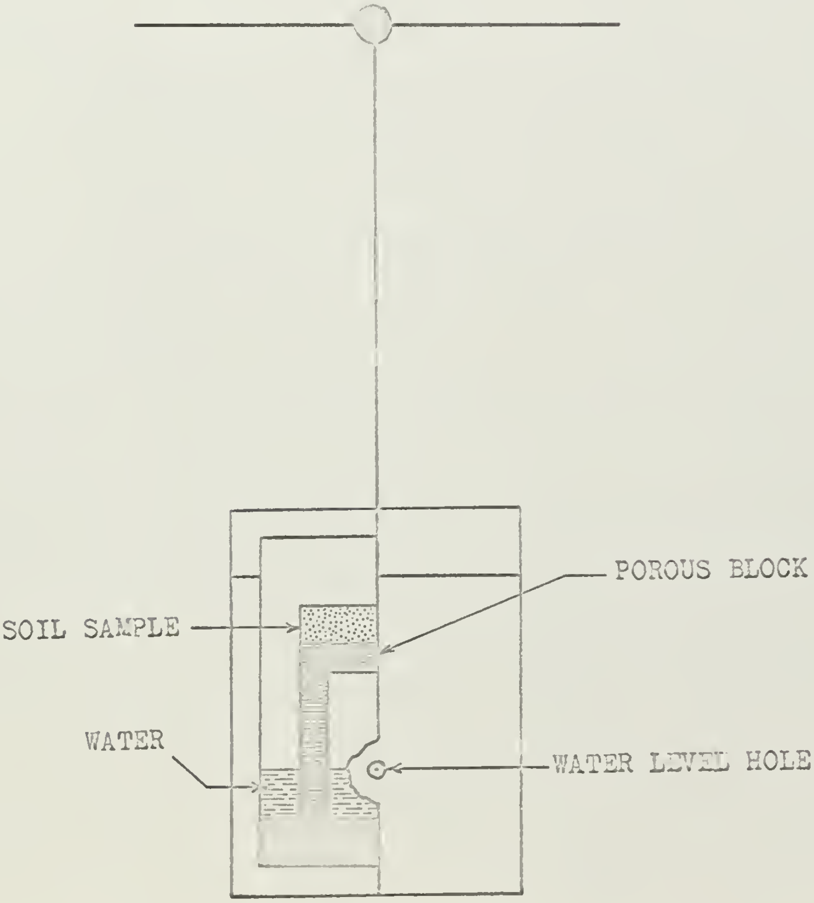
Centrifuge: The centrifuge method, Figure 8, depends on the application of a high gravitational field to a soil sample resting on a porous block. As the sample is centrifuged, the water leaves the soil and is transferred to the constant water level beneath the porous block. The constant water level is maintained by a hole in the side of the centrifuge bottle. The suction obtained is a square root function of the speed of rotation of the centrifuge, therefore, very high speeds are required to obtain suction pressures in excess of pF 4.5. The moisture content of the sample is determined and a moisture content versus soil suction relationship is determined.[19]

Vacuum dessicator: The vacuum dessicator technique, Figure 9, is a method where the soil moisture goes into equilibrium with its surroundings. A suitable dessicant, usually H_2SO_4, with a known specific gravity is present. The specific gravity of the H_2SO_4 will change as it goes into equilibrium with the air and soil above it.



SUCTION PLATE
FIGURE 7

FIGURE 8



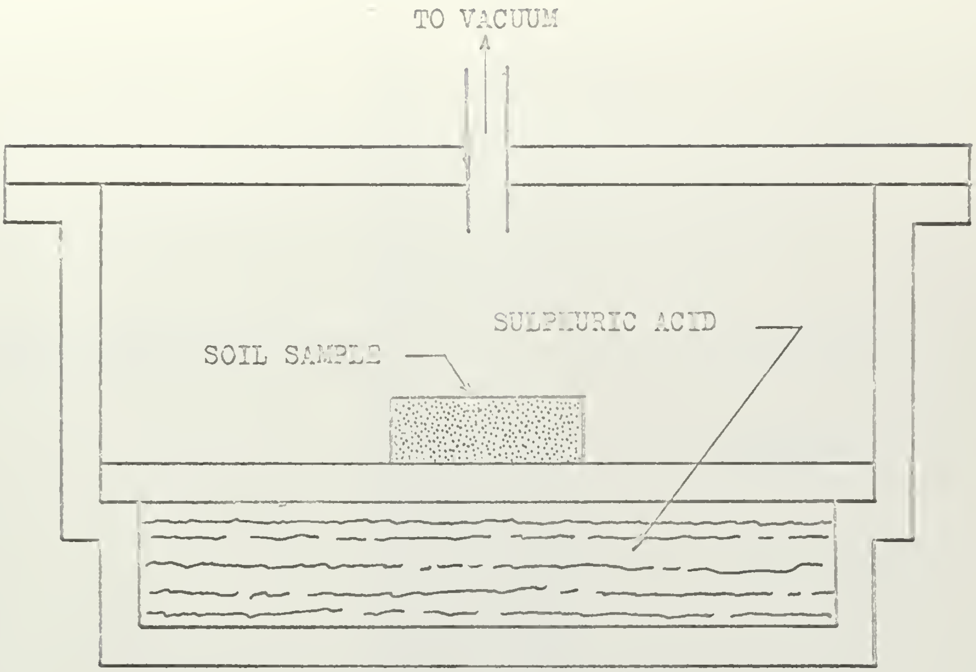
CENTRIFRUGE

The new specific gravity of the H_2SO_4 is determined after equilibrium has been reached and through appropriate tables, the suction of the soil sample is obtained. Extremely precise temperature and humidity controls are necessary in order to make the information obtained of any value at all.[20]

Pressure membrane: The pressure membrane method, Figure 10, is an extension of the suction plate method and permits the observer to obtain greater equilibrium suction pressures. A cellulose membrane is sandwiched between the soil sample and a porous block filled with water at atmospheric temperature. The air pressure above the sample is varied by moving the piston and this applied air pressure is equal to the soil suction in the sample when drainage is complete. This method, using more sophisticated equipment has reached a pF of about 6.2.[21]

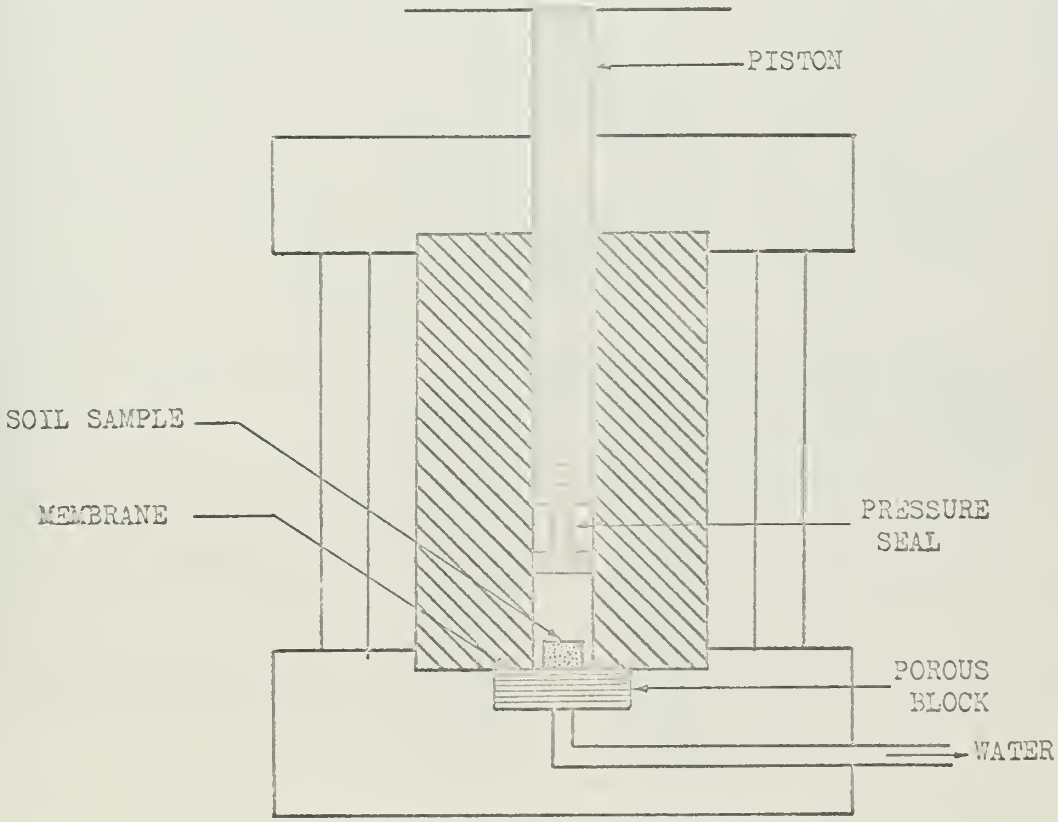
Psychrometer: The psychrometer method, Figure 11, is a relatively new method in the field of pore pressure measurement. Its principle depends on successfully measuring the relative humidity of the air that has come to equilibrium with the soil sample. The relative humidity is a function of soil moisture suction as shown in Figure . The device is calibrated in such a manner that the electrical output of the thermistors is equal to soil suction. The device is quite sensitive to temperature variations. For example, the wet bulb depression of air at 25°C and 99% relative humidity is only 0.13°C. This limitation prevents general field usage of this device.[22]

Gypsum block: The gypsum block method, Figure 12, is basically a system of two electrodes embedded in a porous element whose water content is determined by the pore size distribution of the element. The resistance of the block varies inversely to the soil suction. The block is placed in the soil and a current is passed through it. The electrical output is calibrated to read pF. Some of the problems involved in this method are that each block must be separately calibrated, the gypsum tends to deteriorate with time, and the calibration is sharply affected by soil salinity and temperature.[23]

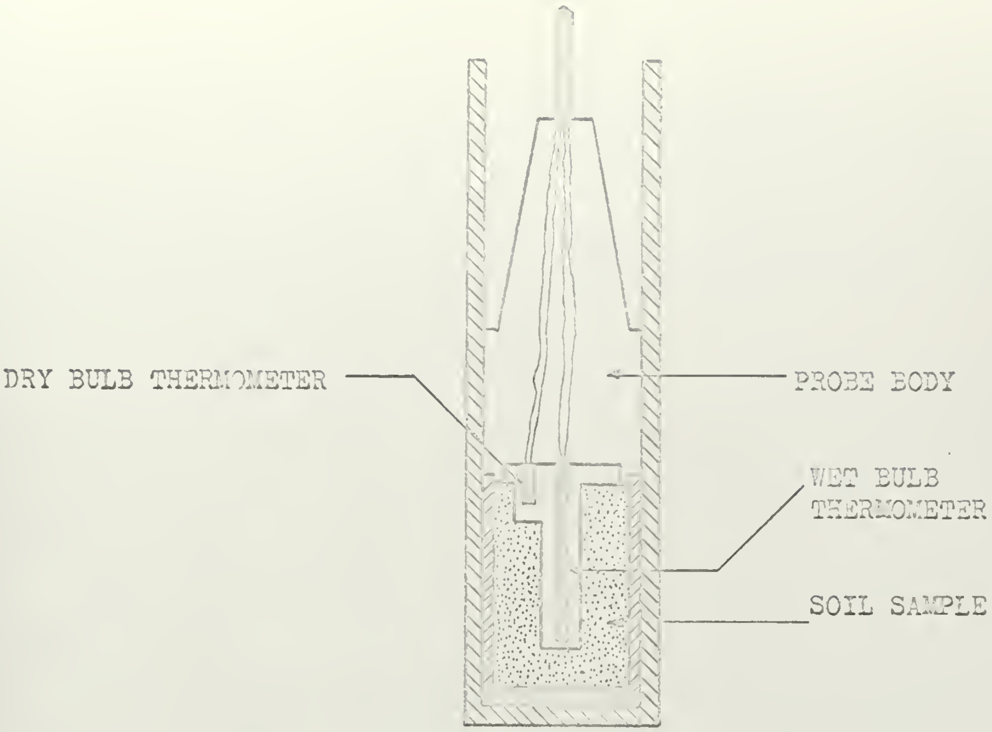


VACUUM DESSICATOR
FIGURE 9

FIGURE 10



PRESSURE MEMBRANE

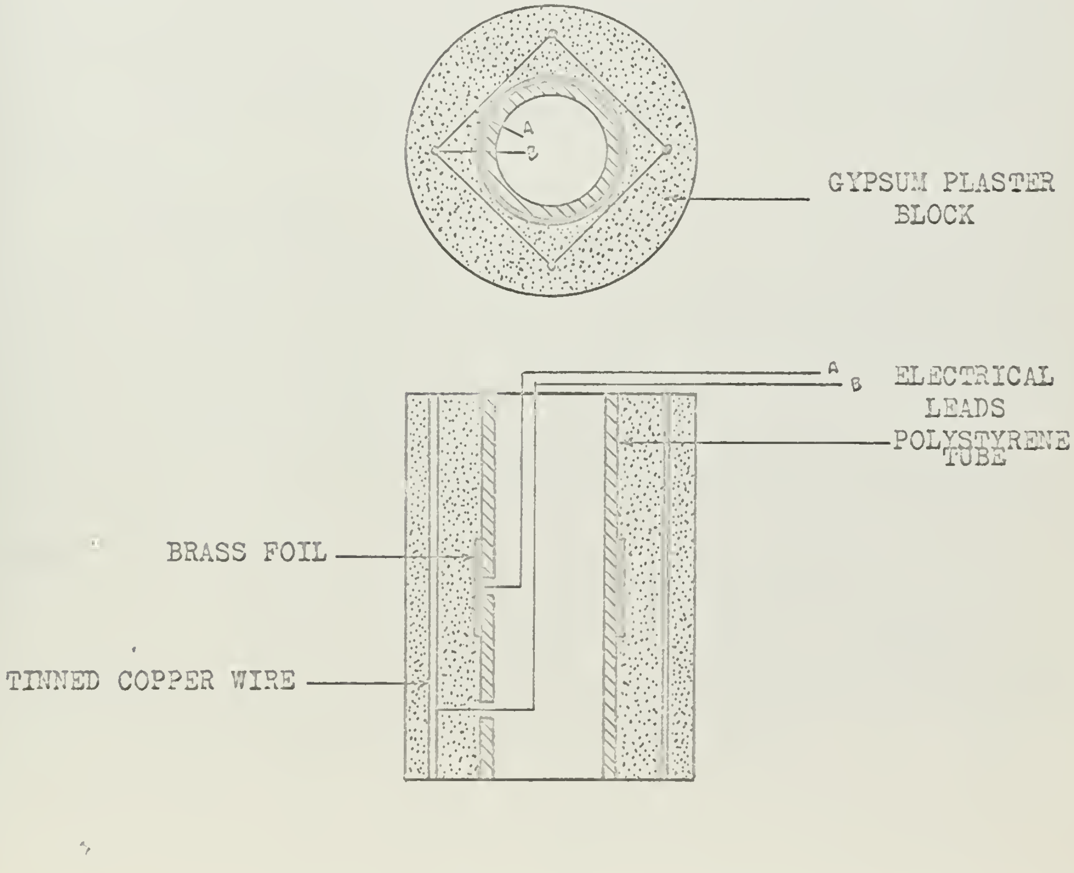


PSYCHROMETER

FIGURE 11

FIGURE 12

GYPSUM BLOCK



Another method used to determine soil suction is to freeze the soil sample. The variation in freezing temperature from that of the freezing temperature of free water is a function of the suction pressure. An equation has been developed to permit the determination of pF directly by observing the depression of the freezing point, (t).

$$pF = 4.1 + \log (t)$$

This method is somewhat restricted though because of the small variations in temperature depression and because the test tends to cause the suction to rise to the highest value compatible with the existing moisture content.[24]

There are many other methods, but most are variations of those described above.

Another method being investigated, is that of conversion of the negative pore water pressures into a positive pressure. Little has been published concerning this method.[25] As mentioned in the INTRODUCTION, there are many chemical compounds that exhibit an affinity for water. Some of these compounds also have a positive volumetric change upon adsorbing water. If such a compound were to be placed next to a soil mass, and a means to prevent the compound from entering the soil were available, the compound would tend to swell, giving the observer an opportunity to measure a positive pressure.

A logical method to separate the soil and the chemical compound is the use of a semi-permeable membrane or the use of osmotic pressure. If the molecular size of the compound is known, one must simply choose a membrane with pores just small enough that it will retain the compound but readily pass water. There are other factors that enter into choosing the best membrane possible:

a. it should be insoluble to the chemicals with which it will be in contact;

b. it should be inert to biological growth;

c. it should be economical and readily available.

In selecting the chemical compound, the following should be considered:

a. it should have large molecular size;

b. it should be inert to biological growth;

c. water adsorption should be rapid and equilibrium should be reached quickly;

d. it should exhibit the least possible internal strain due to variation in applied stress levels;

e. it should readily give up water already adsorbed if the soil mass becomes more dry, thereby changing the free energy level of the soil mass.

OSMOTIC PRESSURE[26]

Osmotic pressure is a phenomenon that depends on the existence of semi-permeable membranes characterized by the fact that they allow one component of a solution to pass through them while they prevent the passage of another. Osmotic pressure of dilute solutions is dependent only on the concentration of the solution and the properties of the solvent. The free energy of the solvent in the solution is less than the free energy of the solvent in pure solvent. Therefore, a spontaneous tendency for the solvent to move from the high free energy to the low free energy of the solution exists. This tendency is balanced by the externally applied pressure known as the osmotic pressure.

The phenomenon of osmosis is thought to be due to any one or a combination of:

a. the membrane acting as a sieve;

b. the chemical component dissolving into the membrane;

c. distillation occuring across the membrane.

Another problem related to osmotic pressure is that of the time it takes to reach equilibrium by diffusion of the water into the chemical. If one were to use a pure chemical solution wi[illegible] dilution, the time required for equilibration would be [illegible] more water per unit volume would have to be taken into the system. Furthermore, by using solutions diluted with water, the volume change will be smaller and the spectrum of positive pressures required to cover the range of pF found in soils will be smaller. This will cause

less stress within the system, a favorable trend when one is working with a chemical that might have a variable stress-strain relationship. One other advantage to using diluted solutions is that it will have a lesser effect on the soil mass immediately adjacent to the system; therefore, the results obtained may be considered to be more typical of the total soil mass.

APPARATUS

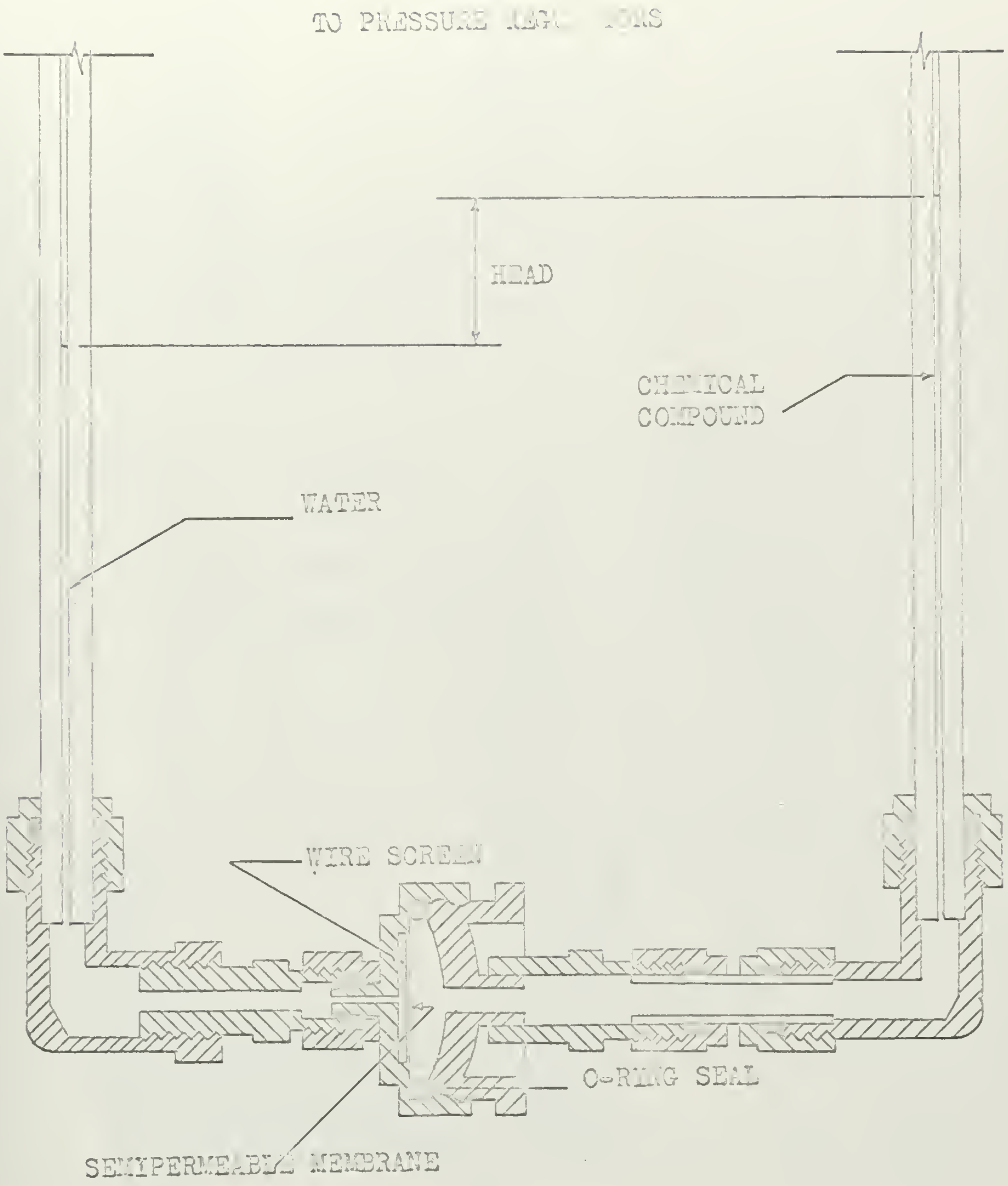
Since this research involved a number of undefined variables, it was decided, in the interest of economy, to attempt to use as preliminary equipment, devices previously designed for other work but suitable for use in this field. This approach permitted economical variable definition.

The central part of the original apparatus is diagrammed in Figure 13. It consisted of the membrane holder, water and chemical compound chambers, and associated connections. A series of these units were manifolded together in order to permit multiple operation with a single pressure differential acting on the two fluid chambers. In order to accommodate the various volume changes that could be expected on different chemicals under the same pressure environment, the water and chemical compound chambers had to be very long. Later investigations proved that these long chambers increased the required time for equilibrium to an unacceptable level. As a result, the chambers were shortened, the chamber-membrane holder connections modified and the manifold system deleted. Subsequent tests with available chemical compounds showed other discrepancies in the design and, as a result of these tests, the apparatus described below appears to be the best method to determine the most suitable chemical compounds and their compatible semi-permeable membranes.

MEMBRANE HOLDER

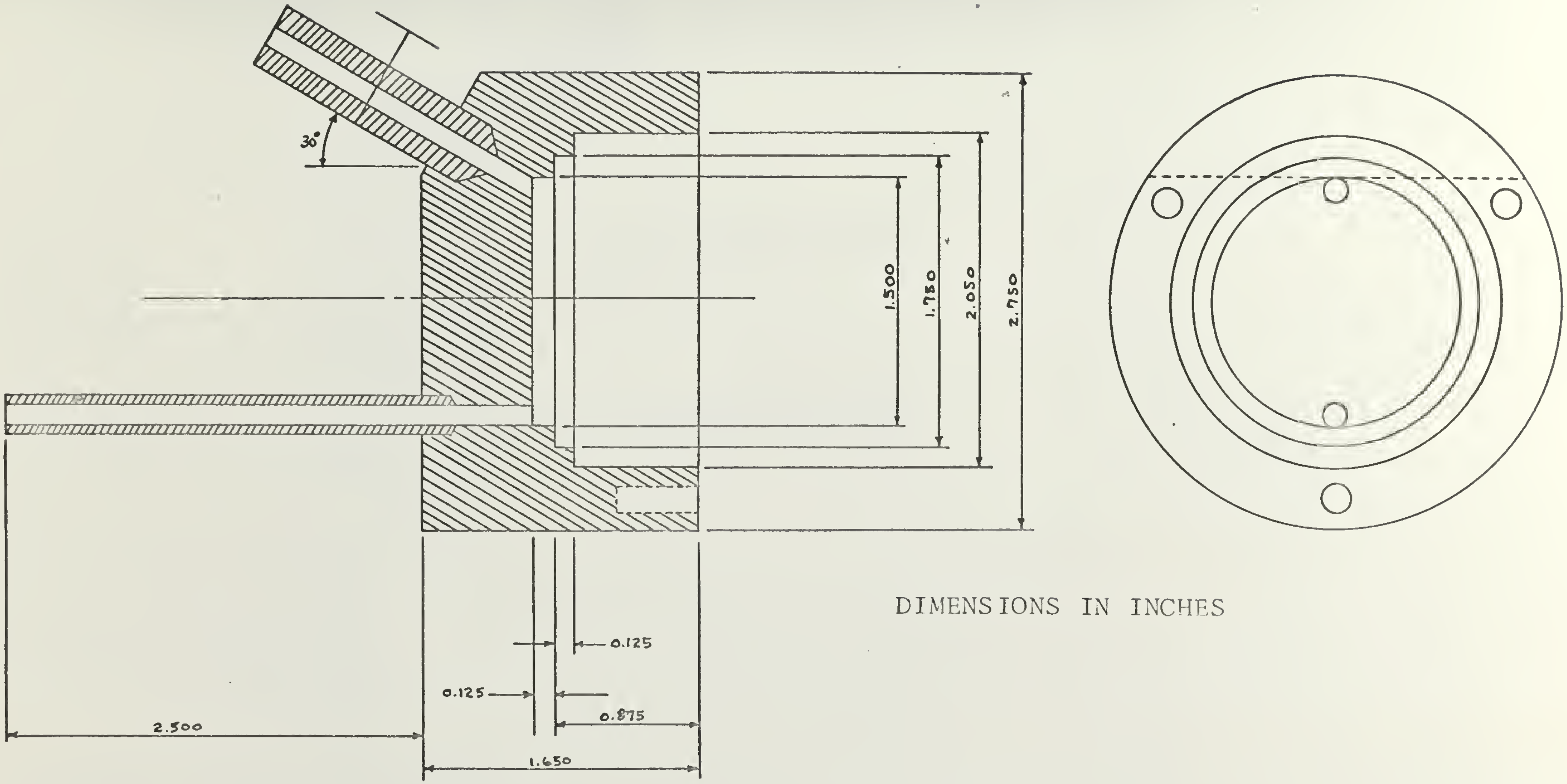
The membrane holder shown in Figures 14-16 was designed expressly for this research effort. It is made of a stainless steel alloy and was milled by the Texas A&M University Engineering Experiment Station. The stainless steel alloy was chosen because of its high resistance to corrosive action by chemicals, thereby permitting its use with a wide assortment of chemical compounds without fear of contamination of the system.

It is extremely important to insure that the membrane holder and the chemical chambers are saturated with their fluids. A small air



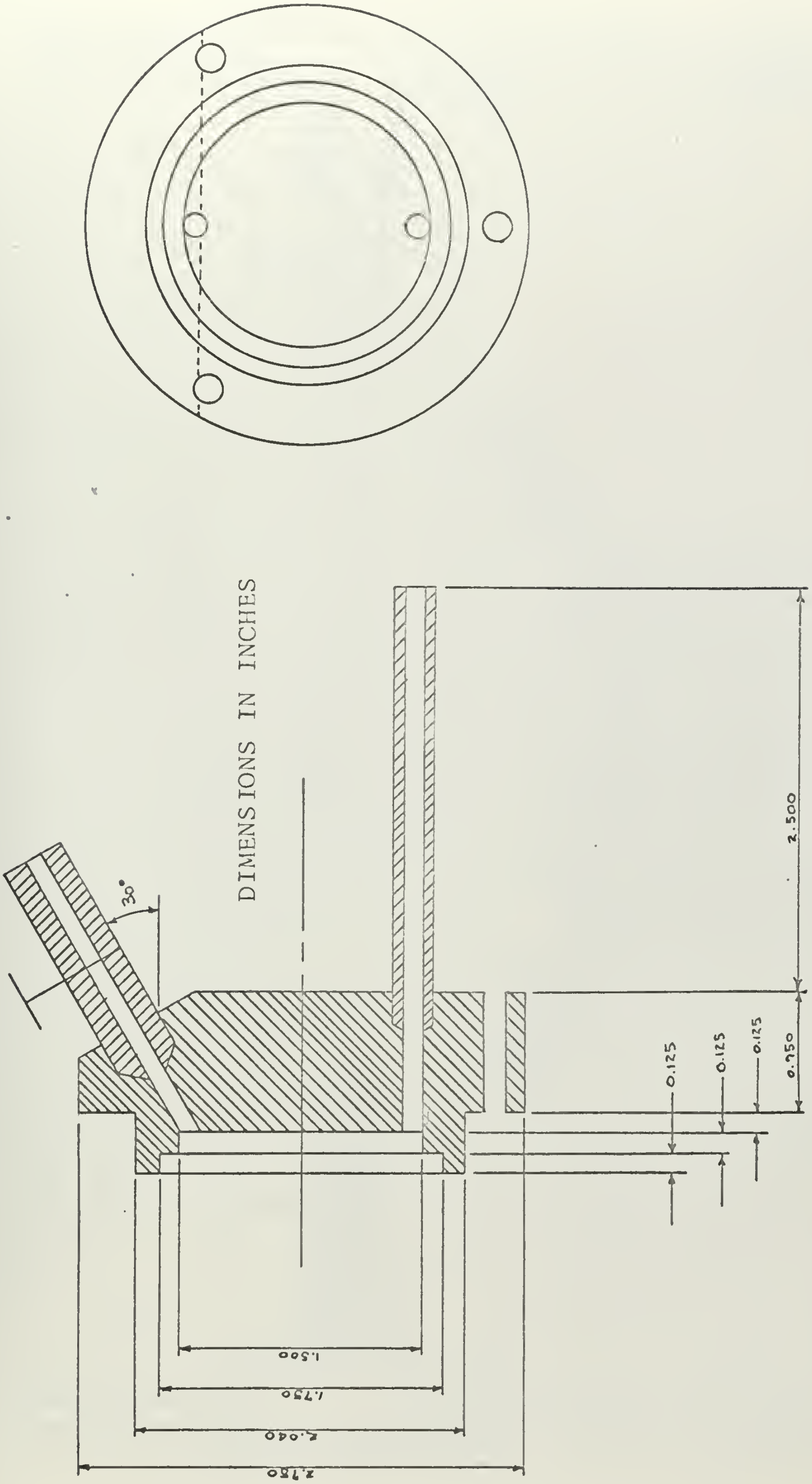
OSMOTIC DEVICE

FIGURE 13



DIMENSIONS IN INCHES

FIGURE 14



DIMENSIONS IN INCHES

FIGURE 15

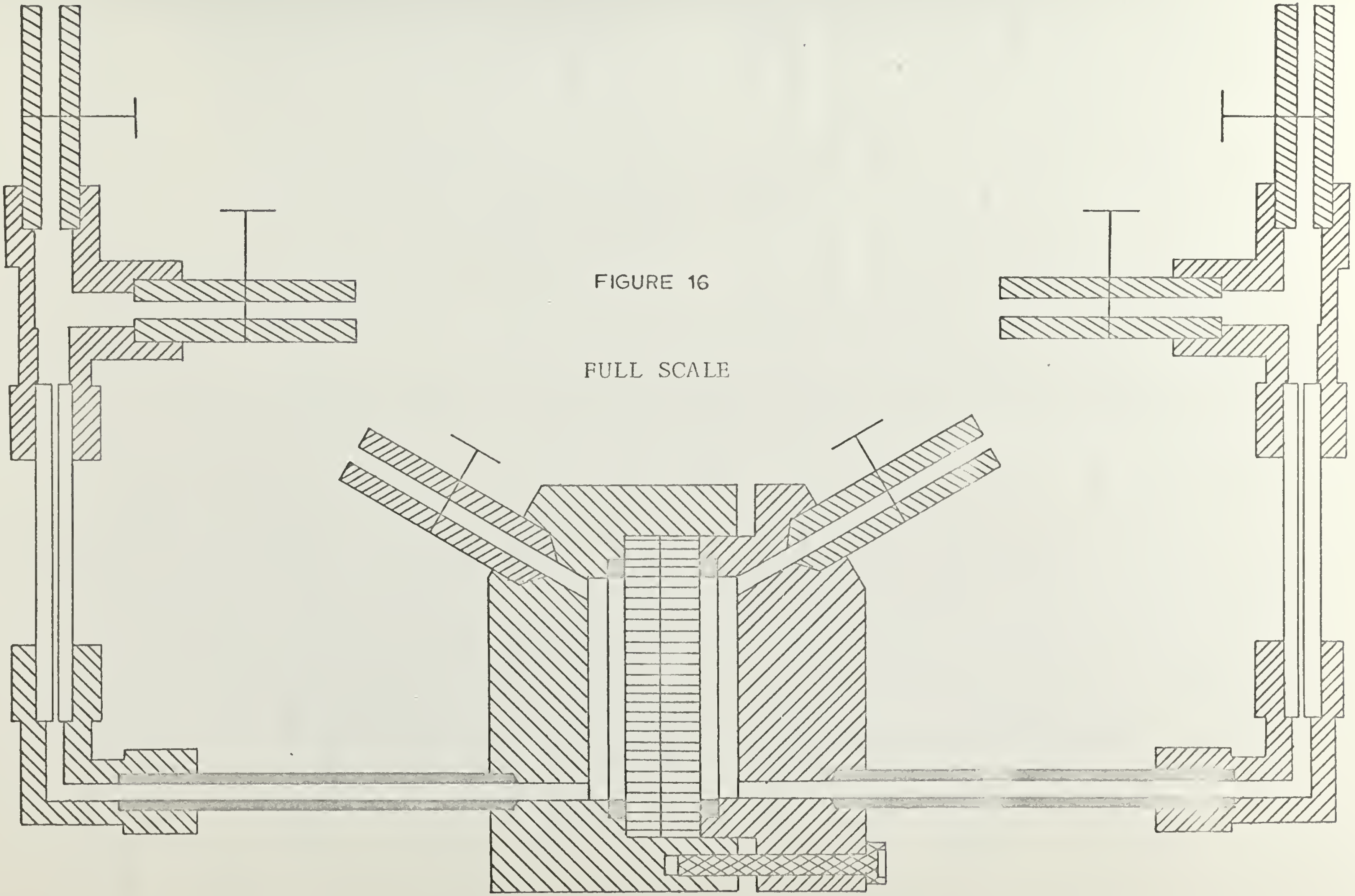


FIGURE 16

FULL SCALE

bubble would cause a radical variation in the fluid height in the attached chemical chamber (see discussion of chemical chamber, following). It is also important that saturation be obtained in order to eliminate problems of reproducibility of results.

The membrane holder was designed to permit positive assurance of saturation. The bleed stop-cock is placed at the top of the device while the feed is placed at the bottom to provide for efficient air removal. Each stop-cock and the stainless steel tubing have been especially fitted into the holder so that there are no places for air entrapment. The bleed stop-cocks are "Circle Seal", no volume change valves. In order to impart rigidity to the membrane used in the system, space is provided for two highly porous ceramic disks, one on either side of the membrane. The system is isolated from the atmosphere by an O-ring on either side of membrane porous disk sandwich. A more detailed discussion of the porous disks follows.

POROUS DISKS

With the design of the membrane holder came the problem of providing for a rigid platform on which the membrane could rest. Machining in such a platform would have made fabrication extremely difficult. By the use of highly porous ceramic disks, as the rigid platform, the machining problem was eliminated. A sealing problem arose to take its place. This problem is taken care of by sealing the membrane between the porous disks with an epoxy resin adhesive. The circumference and a portion of the exposed face of each disk is also coated with the same epoxy resin adhesive. This requires the migration of water to occur only across the semi-permeable membrane. A procedural method discussed in the PROCEDURE of this paper insures saturation of the disks.

CHEMICAL COMPOUND AND WATER CHAMBERS

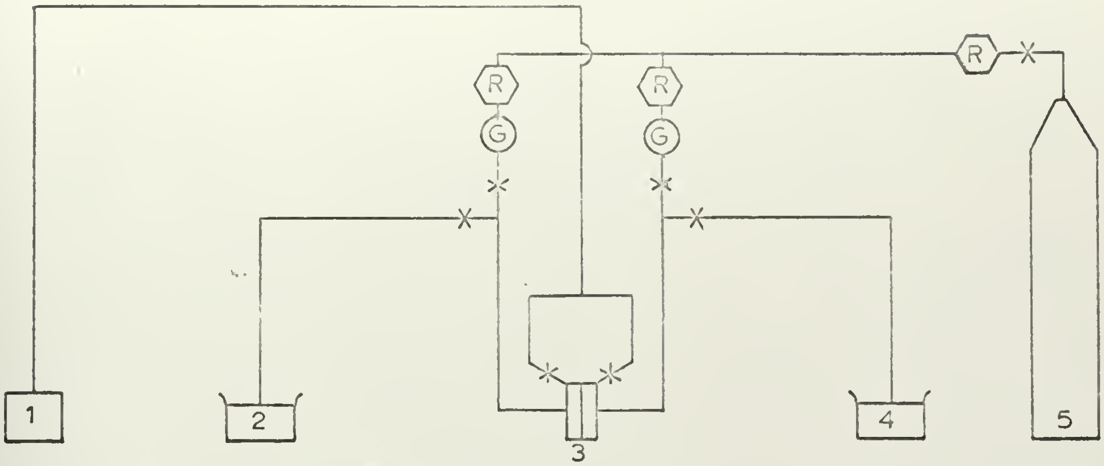
In order to observe the volume changes of the chemical compound and water, heavy duty capillary glass tubing with an ID of 0.75 - 1.25mm and an OD of 6-7mm was chosen. The use of this type chamber develops

a magnification factor since the membrane holder and connections to the chambers constitutes the major volume of the system. A small capillary column not only holds a very small amount of the chemical or water, thereby permitting maximum diffusion mixing in the shortest time, but it also visibly magnifies the volume change by confining it within a very small volume of significant height. Attempts to develop a leakproof system with stainless steel connections between the membrane holder and the glass chambers almost invariably resulted in shattered chambers. This problem was alleviated by the use of a nylon connector between the stainless steel membrane holder and the chambers. The connectors used are Swagelok "Zytel" elbows which not only yield a leakproof system, but are also highly resistant to corrosive chemicals.

PRESSURE SYSTEM

In order to create a variable pF on the system, which indicates whether or not internal strain is of significance, and which permits determining the pF range of the chemical compound being tested, a pressurizing system is necessary. The normal laboratory air system is contaminated with water, oil, and possibly other foreign matter. Bottled nitrogen gas was therefore chosen as the pressurizing medium. The gas delivered to the system is doubly regulated as it passes from the gas bottle, through the Saran 1/4-inch OD tubing into the chambers. A standard NCG style 6501, oxygen regulator is used as the primary regulator releasing the gas under a pressure of $\approx$ 1500psi from the bottle. Just prior to entering the chambers, it is again regulated by Nullmatic pressure regulators Model 40H100 or 40-50 which provide a constant pressure, $\pm$0.5psi, to the system. Pressure gages are Ashcroft AMP 8234 with 1psi subdivisions. A schematic layout of the entire system is shown in Figure 17.

NOT TO SCALE



X - "Circle Seal Stop-cock"
R - Pressure regulator
G - Pressure gage
1 - Vacuum pump

2 -Water reservoir
3 -Membrane holder
4.-Chemical reservoir
5 -Nitrogen supply

FIGURE 17

PROCEDURE

All of the equipment, with the exception of the porous disks and membrane, is rinsed in methyl-ethyl ketone and then washed in a hot distilled water-detergent bath. After a final rinse in distilled water, the pieces were placed in a dessicator to dry.

The porous disks were flushed with hot distilled water prior to being sandwiched together with the membrane. After drying in a dessicator, the disks and membrane were sandwiched together using epoxy resin adhesive. A 24-hour adhesive curing time was allowed, after which the outside adhesive coated edges were smoothed using emory cloth. The disks were placed in the chemical solution and the bottom disk allowed to saturate. When saturation was reached, the porous disks were placed in the membrane holder and the system was closed up. In order to make the equilibrium time required a minimum, consistent with measurable volume changes, the chemical compound was diluted with water. Dilution was on a weight basis.

A vacuum is placed on the chamber through the bleed valves and then the chemical and water feed valves are opened, filling both sides of the chamber. (Since the disks are so porous, the water will quickly fill the disk and all air should be removed. Actually, it is not mandatory that the water side be completely deaired since the main concern is insuring that the chemical side is deaired.) When each side of the chamber is filled, the feed is shut off and each chamber is subjected to a partial vacuum for ten minutes. The bleed valves are then closed and the pressurizing gas is applied. As soon as the pressure is applied the height of the fluid in each chamber is noted. The pressure on the chambers can be varied; indeed, by manipulating the chemical chamber pressure to maintain the same height of fluid, the equilibrium negative pressure is obtained. (It is worthy of note that a rise of approximately 27 inches of water in the capillary column would be the equivalent of 1psi head change.)

[illegible]

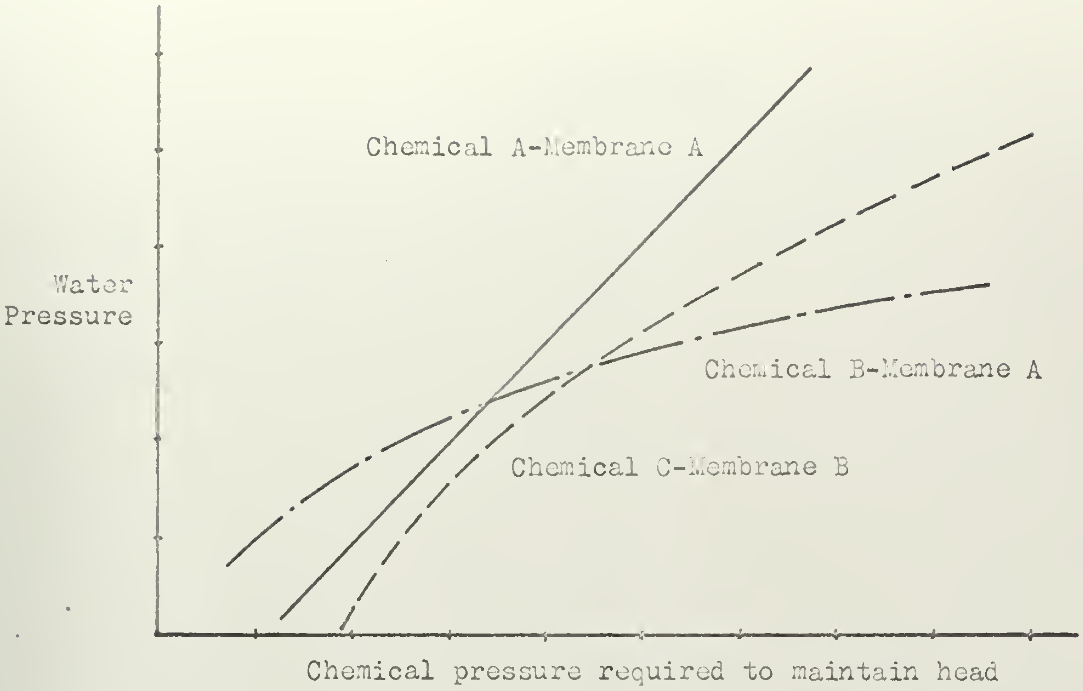
[illegible] to the many problems [illegible] of this type, many results are tentative yet they may still be considered of importance for future research effort.

Originally, there was no [illegible] the amount of the system, the change in [illegible] the average molecular weight of the polymer [illegible] it was virtually impossible to determine the [illegible] [illegible] results [illegible] method [illegible] and [illegible].

[illegible] optical filter [illegible] average pore diameter [illegible] 5 μ. [illegible] solution [illegible] Millipore "HA" filter with [illegible] μ [illegible]. The [illegible] in less than five minutes [illegible]. Subsequent [illegible] μ [illegible], for all practical purposes, the Carbowax-20M flowed freely through the membrane.

Additionally, [illegible] of [illegible] had been used successfully with a "[illegible]" by other researchers in [illegible] was able to [illegible] chemical [illegible].

[illegible] experimental work has been conducted with the [illegible]. Initial experiments are being run with Carbowax-20M and "Plating [illegible]". The Carbowax, a solid at room temperature [illegible] 5 [illegible] (by weight) solution with water. Results, while inconclusive at this point, indicate the necessity of [illegible] to the equipment to obtain [illegible]. Figure 15 [illegible] the results expected in this research effort.


Water Pressure
Chemical A-Membrane A
Chemical B-Membrane A
Chemical C-Membrane B
Chemical pressure required to maintain head

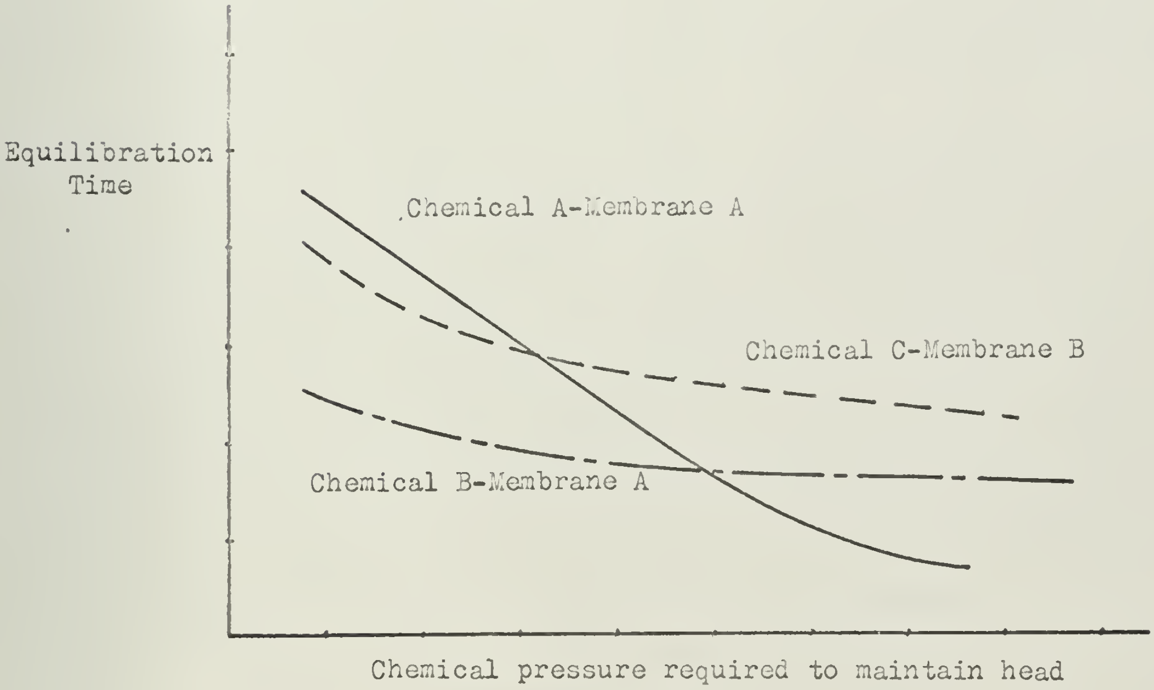

Equilibration Time
Chemical A-Membrane A
Chemical C-Membrane B
Chemical B-Membrane A
Chemical pressure required to maintain head

FIGURE 18

CONCLUSIONS

This writer considers two inter-related problems to be the keys to solving the problem of pressure conversion. The first is finding a compatible chemical and membrane combination; the second is decreasing the equilibration time to a reasonable level. The device shown in Figures 14-16 is considered to be an adequate tool to solve these problems provided certain minor modifications are made.

During the process of conducting this research, it was learned that similar research was being conducted by A. J. Peck and R. M. Rabbidge of CSIRO, Australia.[27] They used Carbowax-20000MW with a dialysis membrane. These gentlemen have submitted a provisional Australian Patent application for a working "in-situ" device. At approximately the same time, correspondence was received from R. J. Millington of the University of Adelaide, Australia, concerning similar work that had been conducted at the University of Illinois in 1965.[28] These experiments used "Visking dialysis membrane" and Carbowax-4000MW. Both of these reports indirectly indicated a certain dissatisfaction in the use of Carbowax and the "Visking dialysis membrane". Some of the objections to using Carbowax-dialysis membrane combination are discussed below.

Carbowax tends to give a generally erratic pressure versus volume change curve, therefore, it is not a totally reliable indicator. Visking membrane, on the other hand, is slightly soluble in water and, over a period of time, it will dissolve. Furthermore, visking membrane has a pore diameter of approximately 0.0048 μ and the water flow rate through this membrane is extremely slow. (In other fields of research, where water and visking membrane are used, equilibration time is of the order of 30 hours.) This time constant automatically built in by the use of visking membrane is hardly acceptable when one considers the possible uses of the proposed system.

The pore size of visking membrane indicates that the Carbowax molecule in the 4000-20000MW has a molecular size not smaller than 0.0048 μ since the membrane retains these chemicals. In order to

decrease the time constant, the chemical molecular size will have to be greatly increased. Many chemicals have been suggested as possible substitutes for Carbowax, mainly because each of them exhibit the hydrophilic tendency desired. Unfortunately, available information indicates that each of them have smaller molecular sizes than the Carbowax molecule. They are mentioned here merely as a safeguard against future research efforts being channeled in their direction: Mannitol, carboxomethylcellulose, alganates, Calcium chloride and gelatin, lithium chloride, magnesium perchlorate, polyvinyl alcohols and various ethers.

As a result of this research effort, this writer considers it necessary for the Chemistry community to fabricate a molecule of suitable size to meet the requirements of this proposed procedure of measuring negative pore pressures. It is considered that a water flow rate through the membrane and the time required for equilibration of the chemical should be such that accurate measurements of the negative pore pressure would be possible in less than two hours. In some specialized cases of research, the time constant should be of the order of minutes, particularly when one is discussing the case of active clays being dessicated.

As far as the actual device for in-situ measurements is concerned, it is this writer's opinion that the pressure measuring portion of the device should be a standard pressure transducer. The membrane chosen to retain the chemical should be protected from direct contact with the soil grains that could cause a rupture of the membrane. The separation could be with the use of a porous ceramic block such as is used in the device to determine the proper chemical-membrane combination. Porous stainless steel could also be investigated. Not only would a porous barrier prevent damage to the membrane but it would also help in alleviating the problem of preventing the transfer of salts found in solution in soil water. The volume of the chemical chamber should be small yet the surface area large in order to permit maximum exposure of the chemical to the vapor pressure of the soil water, thereby reducing the time constant for a given chemical and membrane combination.

RECOMMENDATIONS

The greatest single obstacle to the research conducted by this writer was the lack of access to a qualified chemist who could advise in the field of Chemistry. Since the average Civil Engineer has a limited background in Chemistry, it is recommended that any future research effort in this field be conducted with a designated chemist available for comment and advice.

One of the problems found in the new device is saturation of the chemical chamber/porous block. Although a procedure was developed to theoretically alleviate this problem, saturation is not being obtained. This writer considers that the saturation problem can be solved by:

a. polishing the interior of the chemical chamber;

b. discarding the porous stone and membrane sandwich in favor of a porous stainless steel and membrane sandwich;

c. modifying the feed/pressurizing system.

Another problem is the glass portion of the chemical chamber. The viscosity of the Carbowax-20000MW, when mixed with water, is very high and it tends to stick on the glass chamber walls causing discontinuities in the chemical column. This prohibits positive control of the height of the chemical column, a critical condition. This writer recommends a larger diameter glass chemical chamber to resolve this problem.

It is possible that nitrogen gas (pressurizing medium) is going into solution with the chemical and water. This could effect the results of the research and it is recommended that different pressurizing gases be tried to see if there is a variation in results.

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